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# Search for supersymmetry in pp collisions at $\sqrt{s} = 13$ TeV in the single-lepton final state using the sum of masses of large-radius jets

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## Abstract

Results are reported from a search for supersymmetric particles in proton-proton collisions in the final state with a single lepton; multiple jets, including at least one b-tagged jet; and large missing transverse momentum. The search uses a sample of proton-proton collision data at  $\sqrt{s} = 13$  TeV recorded by the CMS experiment at the LHC, corresponding to an integrated luminosity of  $35.9 \text{ fb}^{-1}$ . The observed event yields in the signal regions are consistent with those expected from standard model backgrounds. The results are interpreted in the context of simplified models of supersymmetry involving gluino pair production, with gluino decay into either on- or off-mass-shell top squarks. Assuming that the top squarks decay into a top quark plus a stable, weakly interacting neutralino, scenarios with gluino masses up to about 1.9 TeV are excluded at 95% confidence level for neutralino masses up to about 1 TeV.

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A central goal of the physics program of the CMS experiment at the CERN LHC [1] is the search for new particles and phenomena beyond the standard model (SM), in particular, for supersymmetry (SUSY) [2–9]. During 2016, CMS recorded a data sample of proton-proton collisions at a center-of-mass energy of 13 TeV, corresponding to an integrated luminosity of  $35.9 \text{ fb}^{-1}$ , significantly extending the sensitivity to the production of new heavy particles. The search described here focuses on a generically important experimental signature that is also strongly motivated by SUSY phenomenology. This signature includes a single lepton (an electron or a muon); several jets, arising from the hadronization of energetic quarks and gluons; at least one b-tagged jet, indicative of processes involving third generation quarks; and, finally,  $\vec{p}_T^{\text{miss}}$ , the missing momentum in the direction transverse to the beam. A large value of  $p_T^{\text{miss}} \equiv |\vec{p}_T^{\text{miss}}|$  can arise from the production of high momentum, weakly interacting particles that escape detection. Searches for SUSY in the single-lepton final state have been performed by both ATLAS and CMS at  $\sqrt{s} = 7$  and 8 TeV [10–13] and at  $\sqrt{s} = 13$  TeV [14–16]. The present analysis, which introduces extended binning and other improvements, is based largely on methodologies described in detail in Ref. [15], which include the use of large-radius jets and related kinematic variables.

In models based on SUSY, new particles are introduced such that all fermionic (bosonic) degrees of freedom in the SM are paired with corresponding bosonic (fermionic) degrees of freedom in the extended theory. The discovery of a Higgs boson with low mass [17–22] provides a key motivation for SUSY. Stabilizing the Higgs boson mass at a low value, without invoking extreme fine tuning of parameters, is a major theoretical challenge, referred to as the gauge hierarchy problem [23–28]. This stabilization can be achieved in so-called natural SUSY models [29–33], in which several of the SUSY partners are constrained to be light [32]: the top squarks,  $\tilde{t}_L$  and  $\tilde{t}_R$ , which have the same electroweak couplings as the left- (L) and right- (R) handed top quarks, respectively; the bottom squark with L-handed couplings ( $\tilde{b}_L$ ); the gluino ( $\tilde{g}$ ); and the higgsinos ( $\tilde{H}$ ). This search targets gluino pair production, which has a relatively large cross section for a given mass, with gluino decay  $\tilde{g} \rightarrow t\bar{t}\tilde{\chi}_1^0$ . This process can arise from  $\tilde{g} \rightarrow \tilde{t}_1\bar{t}$ , where the lighter top squark mass eigenstate  $\tilde{t}_1$  is produced either on or off mass shell. The symbol  $\tilde{\chi}_1^0$  denotes the lightest neutralino, an electrically neutral mass eigenstate that is in general a mixture of the higgsinos and electroweak gauginos. In  $R$ -parity conserving SUSY models [34, 35] in which the  $\tilde{\chi}_1^0$  is the lightest supersymmetric particle (LSP), the  $\tilde{\chi}_1^0$  is stable and can, in principle, account for some or all of the astrophysical dark matter [36–38]. The scenario with off-mass-shell top squarks is denoted as T1tttt [39] in simplified model scenarios [40–42]. In natural SUSY models, the top squark is typically lighter than the gluino, so we also search for scenarios with on-shell top squarks, denoted as T5tttt.

Simulated event samples for SM background processes are used to determine correction factors, typically near unity, that are used in conjunction with observed event yields in control regions to determine the SM background contribution in the signal regions. The production of  $t\bar{t}$ +jets,  $W$ +jets,  $Z$ +jets, and quantum chromodynamics (QCD) multijet events is simulated with the Monte Carlo (MC) generator MADGRAPH5\_aMC@NLO 2.2.2 [43] at leading-order, with parton distribution functions taken from NNPDF 3.0 [44]. Details on the simulated SM background samples, including other processes with smaller contributions (single top quark,  $t\bar{t}$ +bosons, diboson, and  $t\bar{t}t\bar{t}$  production) are given in Ref. [15]. The detector simulation is performed with GEANT4 [45]. Simulated event samples for SUSY signal models are used to determine the selection efficiency for signal events. Because of the large number of mass hypotheses examined in this analysis, the detector simulation in this case is performed with the CMS fast simulation package [46].

Two T1tttt benchmark models are used to illustrate typical signal behavior. The T1tttt(1800,100)

model, which we refer to as a noncompressed-spectrum model (NC), has  $m(\tilde{g}) = 1800$  GeV,  $m(\tilde{\chi}_1^0) = 100$  GeV, and a cross section of 2.8 fb, and corresponds to a scenario with a large gluino-neutralino mass splitting. The T1tttt(1400,1000) model, with  $m(\tilde{g}) = 1400$  GeV,  $m(\tilde{\chi}_1^0) = 1000$  GeV, and a cross section of 25 fb, corresponds to a scenario with a small gluino-neutralino mass splitting and is referred to as a compressed-spectrum model (C).

The data were recorded with the CMS detector [47], which is constructed around a superconducting solenoid of 6 m diameter, providing a magnetic field of 3.8 T. Within the solenoid volume are the charged particle tracking systems, composed of silicon-pixel and silicon-strip detectors, and the calorimeter systems, consisting of a lead tungstate crystal electromagnetic calorimeter (ECAL) and a brass and scintillator hadron calorimeter. Muons are identified and measured by gas-ionization detectors embedded in the magnetic flux-return yoke outside the solenoid. Events were selected using several triggers [48] that require either large  $p_T^{\text{miss}}$  or a single lepton (an electron or a muon), with and without significant hadronic activity. The trigger efficiency is measured in data for our analysis requirements to be nearly 100%.

Event reconstruction proceeds from particles identified by the particle-flow (PF) algorithm [49, 50], which uses information from the tracker, calorimeters, and muon systems to identify PF candidates as electrons, muons, charged or neutral hadrons, or photons. Electrons are reconstructed by associating a charged-particle track with ECAL superclusters [51]. The resulting candidate electrons are required to have transverse momentum  $p_T > 20$  GeV and pseudorapidity  $|\eta| < 2.5$ , and to satisfy identification criteria designed to reject light-parton jets and photon conversions. Muons are reconstructed by associating tracks in the muon system with those found in the silicon tracker [52]. Muon candidates are required to satisfy  $p_T > 20$  GeV and  $|\eta| < 2.4$ . To select leptons from W boson decays, leptons are required to be isolated from other PF candidates. Isolation is quantified using an optimized version [15] of the mini-isolation variable originally suggested in Ref. [53], in which the transverse energy of the particles within a cone around the lepton momentum vector is computed using a cone size that decreases as  $1/p_T^\ell$ , where  $p_T^\ell$  is the transverse momentum of the lepton.

To suppress dilepton backgrounds, we veto events that contain a broader category of candidates for the second lepton, referred to as veto tracks. These include two categories of charged-particle tracks: isolated leptons satisfying looser identification criteria than lepton candidates, including a relaxed momentum requirement,  $p_T > 10$  GeV, and isolated charged-hadron PF candidates, which must satisfy  $p_T > 15$  GeV and  $|\eta| < 2.5$ . In either case, the charge of the veto track must be opposite to that of the lepton candidate in the event. To maintain a high selection efficiency for signal events, lepton veto tracks must satisfy a requirement on the quantity [54, 55]  $M_{T2}(\vec{p}^\ell, \vec{p}_T^v, \vec{p}_T^{\text{miss}}) < 80$  GeV and hadronic veto tracks must satisfy  $M_{T2}(\vec{p}^\ell, \vec{p}_T^v, \vec{p}_T^{\text{miss}}) < 60$  GeV, where  $v$  refers to the veto track.

Charged and neutral PF candidates are clustered into jets using the anti- $k_T$  algorithm [56] with radius parameter  $R = 0.4$ , as implemented in the FASTJET package [57]. Jets are required to satisfy  $p_T > 30$  GeV and  $|\eta| \leq 2.4$ . Additional details and references are given in Ref. [15] on the  $p_T$ - and  $\eta$ -dependent jet energy calibration [58], the jet identification requirements, and the subtraction of the energy contribution to the jet  $p_T$  from multiple proton-proton interactions from the same or neighboring beam crossings (pileup) [59]. A subset of the jets are tagged as originating from b quarks using the combined secondary vertex algorithm [60, 61].

We further cluster the jets with  $R = 0.4$  (small- $R$  jets), including those associated with isolated leptons, into  $R = 1.4$  (large- $R$ ) jets using the anti- $k_T$  algorithm. The masses,  $m(J_i)$ , of the large- $R$  jets reflect the  $p_T$  spectrum and multiplicity of the clustered objects, as well as their angular spread. The variable  $M_J$  is defined as the sum of all large- $R$  jet masses:  $M_J = \sum_{J_i=\text{large-}R \text{ jets}} m(J_i)$ .

For  $t\bar{t}$  events with a small contribution from initial-state radiation (ISR), the  $M_J$  distribution has an approximate cutoff at  $2m_t$ . In contrast, the  $M_J$  distribution for signal events extends to larger values because of the presence of multiple top quarks in the decay chain. The presence of a significant amount of ISR generates a high- $M_J$  tail in the  $t\bar{t}$  background, producing the main source of background in the analysis.

The missing transverse momentum,  $\vec{p}_T^{\text{miss}}$ , is defined as the negative vector sum of the transverse momenta of all PF candidates. To separate backgrounds characterized by the presence of a single W boson decaying leptonically, but without any other source of  $p_T^{\text{miss}}$ , we use the transverse mass  $m_T = \sqrt{2p_T^\ell p_T^{\text{miss}}[1 - \cos(\Delta\phi_{\ell, \vec{p}_T^{\text{miss}}})]}$ , where  $\Delta\phi_{\ell, \vec{p}_T^{\text{miss}}}$  is the difference between the azimuthal angles of  $p_T^\ell$  and  $\vec{p}_T^{\text{miss}}$ . The quantity  $H_T$  is defined as the scalar sum of the transverse momenta of all the small- $R$  jets passing the selection, while  $S_T = H_T + p_T^\ell$ .

We select events with exactly one isolated charged lepton (an electron or a muon), no veto tracks,  $S_T > 500$  GeV,  $p_T^{\text{miss}} > 200$  GeV, and at least six small- $R$  jets, at least one of which is b tagged. After this set of requirements, referred to as the *baseline selection*, about 80% of the SM background arises from  $t\bar{t}$  production. The contributions from events with a single top quark or a W boson in association with jets are each about 6–8%; much of the remainder arises from events with a  $t\bar{t}$  pair produced in association with a vector boson. After applying the baseline selection, the background from QCD multijet events is negligible.

The analysis is performed using four regions in the  $M_J$ - $m_T$  plane: three control regions (CR) and one signal region (SR):

- R1 (CR):  $m_T \leq 140$  GeV,  $250 \leq M_J \leq 400$  GeV,
- R2 (CR):  $m_T \leq 140$  GeV,  $M_J > 400$  GeV,
- R3 (CR):  $m_T > 140$  GeV,  $250 \leq M_J \leq 400$  GeV,
- R4 (SR):  $m_T > 140$  GeV,  $M_J > 400$  GeV.

Regions R2 and R4, which have high  $M_J$ , are divided into bins of  $p_T^{\text{miss}}$ , the number of small- $R$  jets ( $N_{\text{jets}}$ ), and the number of b-tagged jets ( $N_b$ ) as follows:

- three  $p_T^{\text{miss}}$  bins:  $200 < p_T^{\text{miss}} \leq 350$  GeV,  $350 < p_T^{\text{miss}} \leq 500$  GeV,  $p_T^{\text{miss}} > 500$  GeV,
- two  $N_{\text{jets}}$  bins:  $6 \leq N_{\text{jets}} \leq 8$ ,  $N_{\text{jets}} \geq 9$ ,
- three  $N_b$  bins:  $N_b = 1$ ,  $N_b = 2$ ,  $N_b \geq 3$ ,

giving a total of 18 bins each. Backgrounds with a single W boson decaying leptonically are strongly suppressed by the requirement  $m_T > 140$  GeV, so the background in R3 and R4 is dominated by dilepton  $t\bar{t}$  events. Approximately half of the dilepton background events in R4 contain a missed electron or muon, and the other half contain a hadronically decaying  $\tau$  lepton. Given that the main background processes have two or fewer b quarks, the total SM contribution to the  $N_b \geq 3$  bins is very small and is driven by the b tag misidentification rate. Signal events in the T1tttt and T5tttt models populate primarily the bins with  $N_b \geq 2$ .

The method for predicting the background yields takes advantage of the near absence of correlation between the  $M_J$  and  $m_T$  variables in R1–R4, which is a consequence of the high jet multiplicity,  $p_T^{\text{miss}}$ , and  $S_T$  requirements applied in the baseline selection [15]. To satisfy these requirements, background events must typically contain additional jets from ISR. Even though the background at low  $m_T$  arises largely from single-lepton  $t\bar{t}$  events, while the background at high  $m_T$  is dominated by dilepton  $t\bar{t}$  events, the shapes of the  $M_J$  distributions at low and high  $m_T$  become very similar in the presence of multiple ISR jets. We therefore measure this shape at low  $m_T$  (R1, R2) and extrapolate it to high  $m_T$  to obtain the background prediction in R4. The fitted

mean background yields in R1–R4 are thus related by the constraint  $\mu_{R4}^{\text{bkg}} = \kappa \mu_{R3}^{\text{bkg}} \mu_{R2}^{\text{bkg}} / \mu_{R1}^{\text{bkg}}$ . Here,  $\kappa$  is a near-unity correction factor obtained from MC simulation of the total background that accounts for a residual  $m_T$ – $M_J$  correlation:

$$\kappa = \frac{\mu_{R4}^{\text{MC bkg}} / \mu_{R2}^{\text{MC bkg}}}{\mu_{R3}^{\text{MC bkg}} / \mu_{R1}^{\text{MC bkg}}}. \quad (1)$$

This constraint is imposed by relating the expected yields in R1–R4 to three parameters: an overall background normalization  $\lambda$  and two ratios  $R(m_T)$  and  $R(M_J)$ , where the expected background yields are given by  $\mu_{R1}^{\text{bkg}} = \lambda$ ,  $\mu_{R2}^{\text{bkg}} = \lambda R(M_J)$ ,  $\mu_{R3}^{\text{bkg}} = \lambda R(m_T)$ , and  $\mu_{R4}^{\text{bkg}} = \kappa \lambda R(M_J) R(m_T)$ .

We perform two types of maximum likelihood fits, which are described in detail in Ref. [15]. The *predictive fit* uses the observed yields in R1–R3, assuming no signal contribution, to propagate the uncertainties to  $\lambda$ ,  $R(M_J)$ , and  $R(m_T)$ . The *global fit* uses the observed yields in all four regions R1–R4 and allows a signal contribution with a single normalization parameter. The global fit accounts for signal contamination in R1–R3, which is typically less than 10%, and is used to compute signal limits and significances. The results from the predictive fit simplify theoretical reinterpretation in terms of other models by only requiring comparison of observed and predicted yields in R4 rather than all four regions. In both cases, the likelihood function is written as a product of Poisson distributions for the relevant contributions in bins of  $p_T^{\text{miss}}$ ,  $N_{\text{jets}}$ , and  $N_b$  within R2 and R4, taking into account the correlated yields between the unbinned regions R1 and R3.

Systematic uncertainties in the background prediction are incorporated in the uncertainty in the double ratio correction factor  $\kappa$ . Discrepancies between the value of  $\kappa$  predicted by simulation and the true value of  $\kappa$  in the data can in principle arise from mismodeling of the background composition or its properties, including detector effects.

To assess the potential impact of such effects on  $\kappa$ , two control samples in data are used: a 5-jet control sample and a dilepton control sample. The 5-jet control sample is completely dominated by background processes and has an SM composition very similar to that of the analysis regions. In particular, this sample probes the rate at which  $p_T^{\text{miss}}$  is mismeasured in single-lepton events, which could increase the tail of the  $m_T$  distribution. Such events account for about 7% of the background in the signal region at high  $p_T^{\text{miss}}$ . This small event category can have a  $\kappa$  value that departs significantly from unity, and it is important to validate the modeling of such effects. Using the analogous R1–R4 regions in the  $N_{\text{jets}} = 5$  control sample,  $\kappa$  values are measured in data and are found to be consistent with those obtained from simulation. Because of this consistency, the statistical uncertainty obtained from the comparison in the  $N_{\text{jets}} = 5$  control sample is assigned as an uncertainty in  $\kappa$  for each  $p_T^{\text{miss}}$  bin. These uncertainties are taken to be fully correlated over the  $N_{\text{jets}}$  and  $N_b$  bins.

The dilepton control sample is used to test the degree of similarity between the  $M_J$  shapes of single-lepton and dilepton  $t\bar{t}$  events in the presence of ISR. This sample includes not only events with two identified isolated leptons, but also events with one lepton and an oppositely charged veto track. The usual R3 and R4 regions are replaced by dilepton events, and the quantity  $\kappa$  is measured in bins of  $N_{\text{jets}}$ . As in the 5-jets control sample, the values of  $\kappa$  measured in data are found to be consistent with those observed in simulation, and uncertainties are assigned in a similar way. The uncertainties are treated as independent across  $N_{\text{jets}}$  bins but fully correlated across  $N_b$  and  $p_T^{\text{miss}}$  bins. The uncertainties from the dilepton and 5-jet control samples are treated as uncorrelated. Studies of a broad range of potential mismodeling effects in simulation show that all such effects would be evident in these control samples.

Table 1: Observed event yields and mean background yields from the predictive fit in the 18 bins of the signal region R4. Each bin is specified by the values of  $p_T^{\text{miss}}$ ,  $N_{\text{jets}}$ , and  $N_b$ . The uncertainties in  $\kappa$  include both a statistical component from the size of the MC samples and a systematic component assessed from the data control samples. The uncertainty in the predicted event yield includes both of these and the statistical uncertainties associated with the data control regions. Yields for the two T1tttt benchmark models NC and C are also given.

| $N_{\text{jets}}$                              | $N_b$    | NC  | C   | $\kappa$      | Pred.          | Obs. |
|--|----------|-----|-----|---------------|----------------|------|
| $200 < p_T^{\text{miss}} \leq 350 \text{ GeV}$ |          |     |     |               |                |      |
| 6-8  | 1        | 0.4 | 1.9 | $1.2 \pm 0.2$ | $85 \pm 14$    | 106  |
| 6-8  | 2        | 0.6 | 3.0 | $1.2 \pm 0.2$ | $55.1 \pm 9.3$ | 75   |
| 6-8  | $\geq 3$ | 0.6 | 2.2 | $1.5 \pm 0.2$ | $16.4 \pm 3.0$ | 16   |
| $\geq 9$                                       | 1        | 0.2 | 1.6 | $1.0 \pm 0.2$ | $6.5 \pm 1.5$  | 11   |
| $\geq 9$                                       | 2        | 0.3 | 2.1 | $1.2 \pm 0.3$ | $7.6 \pm 1.9$  | 11   |
| $\geq 9$                                       | $\geq 3$ | 0.4 | 3.1 | $1.4 \pm 0.3$ | $2.3 \pm 0.7$  | 2    |
| $350 < p_T^{\text{miss}} \leq 500 \text{ GeV}$ |          |     |     |               |                |      |
| 6-8  | 1        | 0.7 | 1.1 | $1.0 \pm 0.3$ | $17.4 \pm 6.6$ | 25   |
| 6-8  | 2        | 0.9 | 1.3 | $1.1 \pm 0.4$ | $13.7 \pm 5.3$ | 10   |
| 6-8  | $\geq 3$ | 0.8 | 0.9 | $1.3 \pm 0.4$ | $3.8 \pm 1.6$  | 1    |
| $\geq 9$                                       | 1        | 0.3 | 1.0 | $1.1 \pm 0.4$ | $1.3 \pm 0.6$  | 2    |
| $\geq 9$                                       | 2        | 0.5 | 1.1 | $0.8 \pm 0.3$ | $1.6 \pm 0.8$  | 2    |
| $\geq 9$                                       | $\geq 3$ | 0.7 | 2.1 | $1.2 \pm 0.5$ | $0.6 \pm 0.4$  | 0    |
| $p_T^{\text{miss}} > 500 \text{ GeV}$          |          |     |     |               |                |      |
| 6-8  | 1        | 2.5 | 0.6 | $1.0 \pm 0.3$ | $1.9 \pm 1.5$  | 8    |
| 6-8  | 2        | 3.6 | 1.0 | $1.0 \pm 0.4$ | $0.9 \pm 0.7$  | 4    |
| 6-8  | $\geq 3$ | 3.2 | 0.4 | $1.5 \pm 0.6$ | $0.4 \pm 0.4$  | 1    |
| $\geq 9$                                       | 1        | 1.0 | 0.7 | $1.0 \pm 0.4$ | $0.2 \pm 0.2$  | 2    |
| $\geq 9$                                       | 2        | 1.8 | 1.2 | $1.0 \pm 0.4$ | $0.1 \pm 0.1$  | 0    |
| $\geq 9$                                       | $\geq 3$ | 2.3 | 1.7 | $3.1 \pm 1.5$ | $0.1 \pm 0.1$  | 0    |

Systematic uncertainties in the expected signal yields account for uncertainties in the trigger, lepton identification, jet identification, and b tagging efficiencies in simulated data; uncertainties in the distributions of  $p_T^{\text{miss}}$ , number of pileup vertices, and ISR jet multiplicity; and uncertainties in the jet energy corrections, QCD scales, and integrated luminosity [62]. The combined effect of all signal-related uncertainties is typically about 25%.

Table 1 lists the observed event yields in region R4 in data, together with the mean background yields from the predictive fit and the expected signal yields from two benchmark model points. The uncertainties in the predicted background yields include the statistical uncertainties on the event yields in R1–R4 in data, the statistical uncertainties in the  $\kappa$  values arising from the finite size of simulated event samples, and the systematic uncertainties in  $\kappa$  as assessed from the data control samples. The observed yields are consistent with the background predictions in all of the 18 signal bins within 2 standard deviations (s.d.), with most of the 18 bins consistent within 1 s.d. The R4 bins with  $p_T^{\text{miss}} > 500 \text{ GeV}$  show an underprediction of the background with respect to the observed yields. However, accounting for the correlations arising from the use of a single, integrated yield in R3 across bins in  $N_{\text{jets}}$  and  $N_b$ , the significance of the discrepancy in these six bins in R4 is only 1.9 s.d., mostly due to the bins with  $N_b = 1$ .

To simplify the reinterpretation of the results in terms of other theoretical models, we provide predicted mean background yields for four aggregated search bins, shown in Table 2. The aggregate bins are defined such that at least one bin will provide sensitivity to most of the

Table 2: Observed event yields and mean background yields from the predictive fit in four aggregate search bins. In all four cases, the predicted yields refer to the signal region R4 with the standard  $m_T > 140$  GeV and  $M_J > 400$  GeV requirements applied in addition to the baseline selection. Unlike the finely binned approach, where all 18 background predictions are computed simultaneously, the four aggregate bin predictions are computed separately. The aggregate bins overlap, causing their background predictions to be highly correlated. Yields for the two T1tttt benchmark models NC and C are also given.

| $p_T^{\text{miss}}$ [GeV] | $N_{\text{jets}}$ | $N_b$    | NC  | C   | $\kappa$      | Pred.         | Obs. |
|---------------------------|-------------------|----------|-----|-----|---------------|---------------|------|
| $>200$                    | $\geq 9$          | $\geq 3$ | 3.4 | 6.9 | $1.4 \pm 0.3$ | $3.1 \pm 0.8$ | 2    |
| $>350$                    | $\geq 9$          | $\geq 2$ | 5.3 | 6.2 | $1.0 \pm 0.4$ | $2.7 \pm 1.2$ | 2    |
| $>500$                    | $\geq 6$          | $\geq 3$ | 5.4 | 2.1 | $1.7 \pm 0.6$ | $0.5 \pm 0.4$ | 1    |
| $>500$                    | $\geq 9$          | $\geq 1$ | 5.1 | 3.6 | $1.2 \pm 0.4$ | $0.4 \pm 0.4$ | 2    |

models for which the finely binned analysis has sensitivity. Since the aggregate bins overlap, they are intended to be used one at a time, unlike the 18 nonoverlapping signal bins, which are considered simultaneously in the fit. The choice of the best aggregate bin will depend on the properties of the model under consideration. Each prediction includes all sources of uncertainty.

Figure 1 compares the shapes of the  $M_J$  distributions observed in data in the single-lepton sample for  $m_T \leq 140$  GeV and  $m_T > 140$  GeV. In the absence of signal, the shapes of the distributions at low and high  $m_T$  should be consistent, as observed. The lower- $p_T^{\text{miss}}$  region shows the background behavior with higher statistics, while the higher- $p_T^{\text{miss}}$  region has higher sensitivity to the signal.

Figure 2 shows an interpretation of the results as exclusion limits at 95% confidence level (CL) for T1tttt and T5tttt. The limits are obtained using the CL<sub>s</sub> method with a profile-likelihood ratio as the test statistic, using asymptotic approximations for the distribution of the test statistic [63–65]. The color map shows the cross section upper limits as a function of  $m(\tilde{g})$  and  $m(\tilde{\chi}_1^0)$  for T1tttt, assuming a 100% branching fraction for the decay  $\tilde{g} \rightarrow t\bar{t}\tilde{\chi}_1^0$ . The T1tttt model points below the dark solid curve, which extend up to gluino masses of about 1.9 TeV for neutralino masses up to 1 TeV, have a theoretical cross section above the observed cross section upper limit and are thus excluded by this analysis.

Model points below the light solid curve are excluded at 95% CL for the T5tttt model, where it is assumed that the top squark mass is 175 GeV above the neutralino mass, a limiting case in terms of sensitivity to the decay kinematics. For most of the excluded region, the boundaries for T1tttt and T5tttt are very similar, indicating only a weak overall sensitivity to the value of the top squark mass. At low values of  $m(\tilde{\chi}_1^0)$  in T5tttt, the sensitivity is reduced because the neutralino carries very little momentum; however, some sensitivity is still provided by dilepton events that escape the lepton veto [15]. For both the T1tttt and T5tttt models, expected limits are computed using the background-only hypothesis, with nuisance parameters assuming their best fit values from the observed data. All limits are computed using results from the global fit.

In summary, we have performed a search for an excess event yield above that expected for standard model (SM) processes using a data sample of proton-proton collision events with an integrated luminosity of  $35.9 \text{ fb}^{-1}$  at  $\sqrt{s} = 13$  TeV. The signature is characterized by large missing transverse momentum, a single isolated lepton, multiple jets, and at least one b-tagged jet. No significant excesses above the SM backgrounds are observed. The results are interpreted in the framework of simplified models that describe natural supersymmetry (SUSY) scenarios. For gluino pair production followed by the three-body decay  $\tilde{g} \rightarrow t\bar{t}\tilde{\chi}_1^0$  (T1tttt model), gluinos



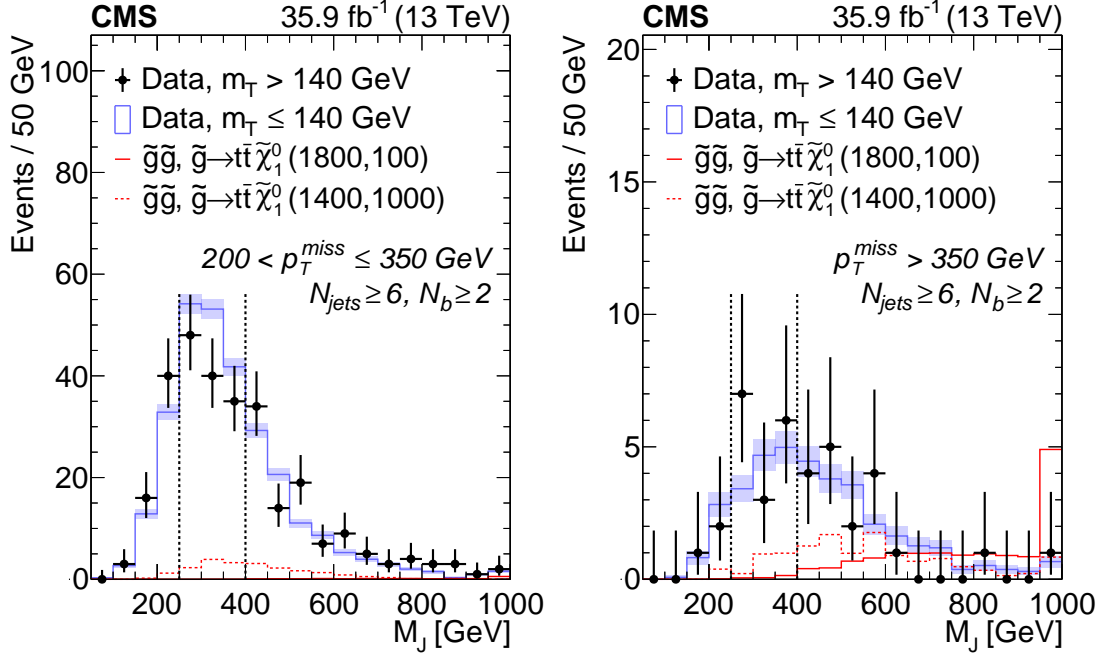


Figure 1: Distributions of  $M_J$  observed in data for  $200 < p_T^{\text{miss}} \leq 350$  GeV (left) and  $p_T^{\text{miss}} > 350$  GeV (right) with the baseline selection and either  $m_T \leq 140$  GeV or  $m_T > 140$  GeV. In each plot, the data at low  $m_T$  have been normalized to the yield observed at high  $m_T$ . The vertical dashed lines at  $M_J = 250$  GeV and  $400$  GeV show the boundaries separating the control and signal regions. The data are integrated over  $N_{\text{jets}} \geq 6$  and  $N_b \geq 2$ . Two SUSY benchmark models, whose contributions are small in the lower  $p_T^{\text{miss}}$  region, are shown in the solid and dashed red histograms. Overflow events are included in the uppermost bins.

with masses below 1.9 TeV are excluded at 95% confidence level for neutralino masses up to about 1 TeV. For the two-body gluino decay  $\tilde{g} \rightarrow \tilde{t}_1 \bar{t}$  with  $\tilde{t}_1 \rightarrow t \tilde{\chi}_1^0$  (T5tttt model), the results are generally similar, except at low neutralino masses, where the excluded gluino mass is somewhat lower. These results extend previous gluino mass limits by about 300 GeV and are among the most stringent constraints on these simplified models of SUSY to date.

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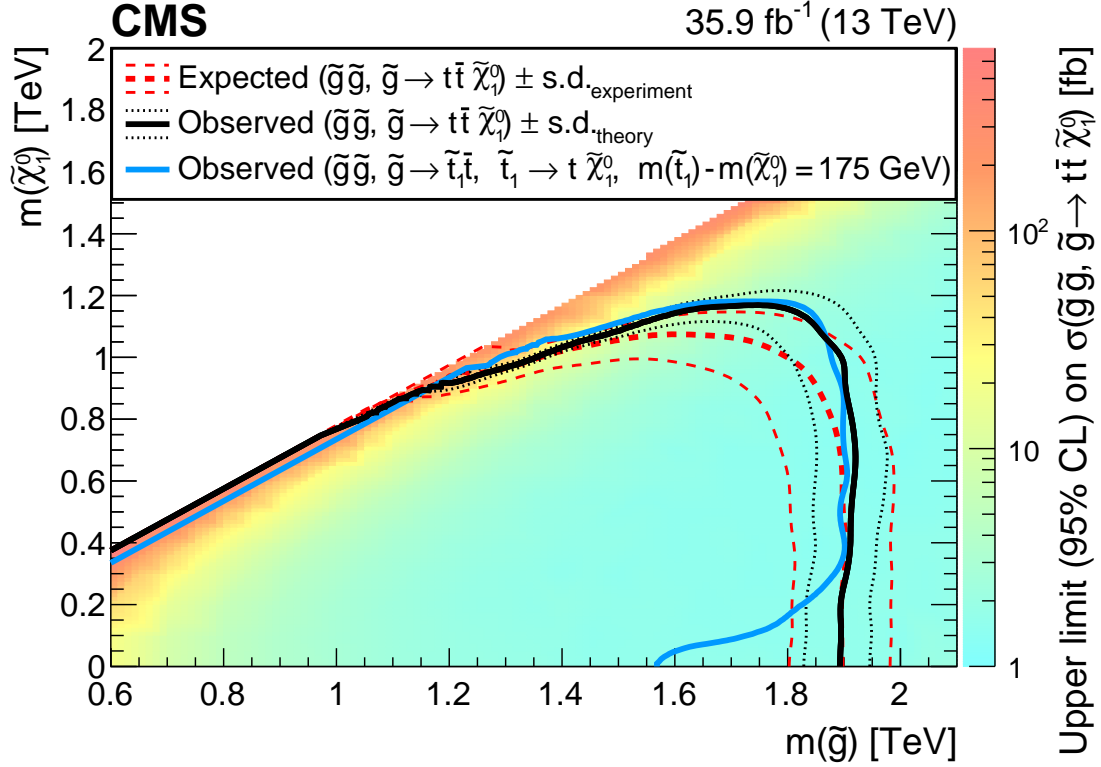


Figure 2: Excluded gluino and neutralino masses at 95% CL for the T1tttt (black, dark solid) and T5tttt (blue, light solid) models. The dashed red lines show the expected exclusion for the T1tttt model. The color map shows the observed cross section upper limits for the T1tttt model. The theoretical uncertainties in the T5tttt exclusion curve are similar to those for T1tttt.

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## References

- [1] L. Evans and P. Bryant, “LHC Machine”, *JINST* **3** S08001, doi:10.1088/1748-0221/3/08/S08001.
- [2] P. Ramond, “Dual theory for free fermions”, *Phys. Rev. D* **3** (1971) 2415, doi:10.1103/PhysRevD.3.2415.
- [3] Y. A. Golfand and E. P. Likhtman, “Extension of the algebra of Poincaré group generators and violation of P invariance”, *JETP Lett.* **13** (1971) 323.
- [4] A. Neveu and J. H. Schwarz, “Factorizable dual model of pions”, *Nucl. Phys. B* **31** (1971) 86, doi:10.1016/0550-3213(71)90448-2.
- [5] D. V. Volkov and V. P. Akulov, “Possible universal neutrino interaction”, *JETP Lett.* **16** (1972) 438.
- [6] J. Wess and B. Zumino, “A lagrangian model invariant under supergauge transformations”, *Phys. Lett. B* **49** (1974) 52, doi:10.1016/0370-2693(74)90578-4.

- [7] J. Wess and B. Zumino, “Supergauge transformations in four dimensions”, *Nucl. Phys. B* **70** (1974) 39, doi:10.1016/0550-3213(74)90355-1.
- [8] P. Fayet, “Supergauge invariant extension of the Higgs mechanism and a model for the electron and its neutrino”, *Nucl. Phys. B* **90** (1975) 104, doi:10.1016/0550-3213(75)90636-7.
- [9] H. P. Nilles, “Supersymmetry, supergravity and particle physics”, *Phys. Rep.* **110** (1984) 1, doi:10.1016/0370-1573(84)90008-5.
- [10] ATLAS Collaboration, “Search for supersymmetry in final states with jets, missing transverse momentum and one isolated lepton in  $\sqrt{s} = 7$  TeV pp collisions using 1 fb<sup>-1</sup> of ATLAS data”, *Phys. Rev. D* **85** (2012) 012006, doi:10.1103/PhysRevD.85.012006, arXiv:1109.6606. [Erratum: doi:10.1103/PhysRevD.87.099903].
- [11] ATLAS Collaboration, “Search for squarks and gluinos in events with isolated leptons, jets and missing transverse momentum at  $\sqrt{s} = 8$  TeV with the ATLAS detector”, *JHEP* **04** (2015) 116, doi:10.1007/JHEP04(2015)116, arXiv:1501.03555.
- [12] CMS Collaboration, “Search for supersymmetry in pp collisions at  $\sqrt{s} = 7$  TeV in events with a single lepton, jets, and missing transverse momentum”, *JHEP* **08** (2011) 156, doi:10.1007/JHEP08(2011)156, arXiv:1107.1870.
- [13] CMS Collaboration, “Search for supersymmetry in pp collisions at  $\sqrt{s} = 8$  TeV in events with a single lepton, large jet multiplicity, and multiple b jets”, *Phys. Lett. B* **733** (2014) 328, doi:10.1016/j.physletb.2014.04.023, arXiv:1311.4937.
- [14] ATLAS Collaboration, “Search for gluinos in events with an isolated lepton, jets and missing transverse momentum at  $\sqrt{s} = 13$  TeV with the ATLAS detector”, *Eur. Phys. J. C* **76** (2016) 565, doi:10.1140/epjc/s10052-016-4397-x, arXiv:1605.04285.
- [15] CMS Collaboration, “Search for supersymmetry in pp collisions at  $\sqrt{s} = 13$  TeV in the single-lepton final state using the sum of masses of large-radius jets”, *JHEP* **08** (2016) 122, doi:10.1007/JHEP08(2016)122, arXiv:1605.04608.
- [16] CMS Collaboration, “Search for supersymmetry in events with one lepton and multiple jets in proton-proton collisions at  $\sqrt{s} = 13$  TeV”, *Phys. Rev. D* **95** (2017) 012011, doi:10.1103/PhysRevD.95.012011, arXiv:1609.09386.
- [17] ATLAS Collaboration, “Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC”, *Phys. Lett. B* **716** (2012) 1, doi:10.1016/j.physletb.2012.08.020, arXiv:1207.7214.
- [18] CMS Collaboration, “Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC”, *Phys. Lett. B* **716** (2012) 30, doi:10.1016/j.physletb.2012.08.021, arXiv:1207.7235.
- [19] CMS Collaboration, “Observation of a new boson with mass near 125 GeV in pp collisions at  $\sqrt{s} = 7$  and 8 TeV”, *JHEP* **06** (2013) 081, doi:10.1007/JHEP06(2013)081, arXiv:1303.4571.
- [20] CMS Collaboration, “Precise determination of the mass of the Higgs boson and tests of compatibility of its couplings with the standard model predictions using proton collisions at 7 and 8 TeV”, *Eur. Phys. J. C* **75** (2015) 212, doi:10.1140/epjc/s10052-015-3351-7, arXiv:1412.8662.

- [21] ATLAS Collaboration, “Measurement of the Higgs boson mass from the  $H \rightarrow \gamma\gamma$  and  $H \rightarrow ZZ^* \rightarrow 4\ell$  channels with the ATLAS detector using  $25 \text{ fb}^{-1}$  of  $pp$  collision data”, *Phys. Rev. D* **90** (2014) 052004, doi:10.1103/PhysRevD.90.052004, arXiv:1406.3827.
- [22] ATLAS and CMS Collaborations, “Combined Measurement of the Higgs Boson Mass in  $pp$  Collisions at  $\sqrt{s} = 7$  and 8 TeV with the ATLAS and CMS Experiments”, *Phys. Rev. Lett.* **114** (2015) 191803, doi:10.1103/PhysRevLett.114.191803, arXiv:1503.07589.
- [23] G. 't Hooft, “Naturalness, chiral symmetry, and spontaneous chiral symmetry breaking”, *NATO Sci. Ser. B* **59** (1980) 135.
- [24] E. Witten, “Dynamical breaking of supersymmetry”, *Nucl. Phys. B* **188** (1981) 513, doi:10.1016/0550-3213(81)90006-7.
- [25] M. Dine, W. Fischler, and M. Srednicki, “Supersymmetric technicolor”, *Nucl. Phys. B* **189** (1981) 575, doi:10.1016/0550-3213(81)90582-4.
- [26] S. Dimopoulos and S. Raby, “Supercolor”, *Nucl. Phys. B* **192** (1981) 353, doi:10.1016/0550-3213(81)90430-2.
- [27] S. Dimopoulos and H. Georgi, “Softly broken supersymmetry and SU(5)”, *Nucl. Phys. B* **193** (1981) 150, doi:10.1016/0550-3213(81)90522-8.
- [28] R. K. Kaul and P. Majumdar, “Cancellation of quadratically divergent mass corrections in globally supersymmetric spontaneously broken gauge theories”, *Nucl. Phys. B* **199** (1982) 36, doi:10.1016/0550-3213(82)90565-X.
- [29] R. Barbieri and G. F. Giudice, “Upper bounds on supersymmetric particle masses”, *Nucl. Phys. B* **306** (1988) 63, doi:10.1016/0550-3213(88)90171-X.
- [30] S. Dimopoulos and G. F. Giudice, “Naturalness constraints in supersymmetric theories with nonuniversal soft terms”, *Phys. Lett. B* **357** (1995) 573, doi:10.1016/0370-2693(95)00961-J, arXiv:hep-ph/9507282.
- [31] R. Barbieri and D. Pappadopulo, “S-particles at their naturalness limits”, *JHEP* **10** (2009) 061, doi:10.1088/1126-6708/2009/10/061, arXiv:0906.4546.
- [32] M. Papucci, J. T. Ruderman, and A. Weiler, “Natural SUSY endures”, *JHEP* **09** (2012) 035, doi:10.1007/JHEP09(2012)035, arXiv:1110.6926.
- [33] J. L. Feng, “Naturalness and the Status of Supersymmetry”, *Ann. Rev. Nucl. Part. Sci.* **63** (2013) 351, doi:10.1146/annurev-nucl-102010-130447, arXiv:1302.6587.
- [34] G. R. Farrar and P. Fayet, “Phenomenology of the production, decay, and detection of new hadronic states associated with supersymmetry”, *Phys. Lett. B* **76** (1978) 575, doi:10.1016/0370-2693(78)90858-4.
- [35] S. P. Martin, “A supersymmetry primer”, *Adv. Ser. Direct. High Energy Phys.* **18** (1998) 1, doi:10.1142/9789812839657\_0001, arXiv:hep-ph/9709356.
- [36] F. Zwicky, “Die Rotverschiebung von extragalaktischen Nebeln”, *Helv. Phys. Acta* **6** (1933) 110.

- [37] V. C. Rubin and W. K. Ford Jr, “Rotation of the Andromeda Nebula from a Spectroscopic Survey of Emission Regions”, *Astrophys. J.* **159** (1970) 379, doi:10.1086/150317.
- [38] Particle Data Group Collaboration, “Review of Particle Physics”, *Chin. Phys. C* **40** (2016), no. 10, 100001, doi:10.1088/1674-1137/40/10/100001.
- [39] CMS Collaboration, “Interpretation of searches for supersymmetry with simplified models”, *Phys. Rev. D* **88** (2013) 052017, doi:10.1103/PhysRevD.88.052017, arXiv:1301.2175.
- [40] J. Alwall, P. Schuster, and N. Toro, “Simplified models for a first characterization of new physics at the LHC”, *Phys. Rev. D* **79** (2009) 075020, doi:10.1103/PhysRevD.79.075020, arXiv:0810.3921.
- [41] J. Alwall, M.-P. Le, M. Lisanti, and J. G. Wacker, “Model-independent jets plus missing energy searches”, *Phys. Rev. D* **79** (2009) 015005, doi:10.1103/PhysRevD.79.015005, arXiv:0809.3264.
- [42] D. Alves et al., “Simplified models for LHC new physics searches”, *J. Phys. G* **39** (2012) 105005, doi:10.1088/0954-3899/39/10/105005, arXiv:1105.2838.
- [43] J. Alwall et al., “The automated computation of tree-level and next-to-leading order differential cross sections, and their matching to parton shower simulations”, *JHEP* **07** (2014) 079, doi:10.1007/JHEP07(2014)079, arXiv:1405.0301.
- [44] NNPDF Collaboration, “Parton distributions for the LHC Run II”, *JHEP* **04** (2015) 040, doi:10.1007/JHEP04(2015)040, arXiv:1410.8849.
- [45] GEANT4 Collaboration, “GEANT4 — a simulation toolkit”, *Nucl. Instrum. Meth. A* **506** (2003) 250, doi:10.1016/S0168-9002(03)01368-8.
- [46] CMS Collaboration, “The fast simulation of the CMS detector at LHC”, *J. Phys. Conf. Ser.* **331** (2011) 032049, doi:10.1088/1742-6596/331/3/032049.
- [47] CMS Collaboration, “The CMS experiment at the CERN LHC”, *JINST* **3** (2008) S08004, doi:10.1088/1748-0221/3/08/S08004.
- [48] CMS Collaboration, “The CMS trigger system”, *JINST* **12** (2017), no. 01, P01020, doi:10.1088/1748-0221/12/01/P01020, arXiv:1609.02366.
- [49] CMS Collaboration, “Particle flow event reconstruction in CMS and performance for jets, taus and  $E_T^{\text{miss}}$ ”, CMS Physics Analysis Summary CMS-PAS-PFT-09-001, CERN, 2009.
- [50] CMS Collaboration, “Commissioning of the particle-flow event reconstruction with the first LHC collisions recorded in the CMS detector”, CMS Physics Analysis Summary CMS-PAS-PFT-10-001, CERN, 2010.
- [51] CMS Collaboration, “Performance of electron reconstruction and selection with the CMS detector in proton-proton collisions at  $\sqrt{s} = 8$  TeV”, *JINST* **10** (2015) P06005, doi:10.1088/1748-0221/10/06/P06005, arXiv:1502.02701.
- [52] CMS Collaboration, “Performance of CMS muon reconstruction in pp collision events at  $\sqrt{s} = 7$  TeV”, *JINST* **7** (2012) P10002, doi:10.1088/1748-0221/7/10/P10002, arXiv:1206.4071.

- [53] K. Rehermann and B. Tweedie, “Efficient identification of boosted semileptonic top quarks at the LHC”, *JHEP* **03** (2011) 059, doi:10.1007/JHEP03(2011)059, arXiv:1007.2221.
- [54] C. G. Lester and D. J. Summers, “Measuring masses of semi-invisibly decaying particle pairs produced at hadron colliders”, *Phys. Lett. B* **463** (1999) 5, doi:10.1016/S0370-2693(99)00945-4.
- [55] A. Barr, C. Lester, and P. Stephens, “A variable for measuring masses at hadron colliders when missing energy is expected;  $m_{T2}$ : the truth behind the glamour”, *J. Phys. G* **29** (2003) 2343, doi:10.1088/0954-3899/29/10/304, arXiv:hep-ph/0304226.
- [56] M. Cacciari, G. P. Salam, and G. Soyez, “The anti- $k_t$  jet clustering algorithm”, *JHEP* **04** (2008) 063, doi:10.1088/1126-6708/2008/04/063, arXiv:0802.1189.
- [57] M. Cacciari, G. P. Salam, and G. Soyez, “FastJet user manual”, *Eur. Phys. J. C* **72** (2012) 1896, doi:10.1140/epjc/s10052-012-1896-2, arXiv:1111.6097.
- [58] CMS Collaboration, “Determination of jet energy calibration and transverse momentum resolution in CMS”, *JINST* **6** (2011) P11002, doi:10.1088/1748-0221/6/11/P11002, arXiv:1107.4277.
- [59] M. Cacciari and G. P. Salam, “Pileup subtraction using jet areas”, *Phys. Lett. B* **659** (2008) 119, doi:10.1016/j.physletb.2007.09.077, arXiv:0707.1378.
- [60] CMS Collaboration, “Identification of b-quark jets with the CMS experiment”, *JINST* **8** (2013) P04013, doi:10.1088/1748-0221/8/04/P04013, arXiv:1211.4462.
- [61] CMS Collaboration, “Identification of b quark jets at the CMS Experiment in the LHC Run 2”, CMS Physics Analysis Summary CMS-PAS-BTV-15-001, CERN, 2016.
- [62] CMS Collaboration, “CMS Luminosity Measurements for the 2016 Data Taking Period”, CMS Physics Analysis Summary CMS-PAS-LUM-17-001, CERN, 2017.
- [63] A. L. Read, “Presentation of search results: The  $CL_s$  technique”, *J. Phys. G* **28** (2002) 2693, doi:10.1088/0954-3899/28/10/313.
- [64] ATLAS and CMS Collaborations, LHC Higgs Combination Group, “Procedure for the LHC Higgs boson search combination in Summer 2011”, Technical Report CMS-NOTE-2011-005, ATL-PHYS-PUB-2011-11, CERN, 2011.
- [65] G. Cowan, K. Cranmer, E. Gross, and O. Vitells, “Asymptotic formulae for likelihood-based tests of new physics”, *Eur. Phys. J. C* **71** (2011) 1554, doi:10.1140/epjc/s10052-011-1554-0, arXiv:1007.1727. [Erratum: doi:10.1140/epjc/s10052-013-2501-z].

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